REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
01-01-2014	Final Report	1-Mar-2012 - 30-Sep-2013

4. TITLE AND SUBTITLE
Measurement Science of the Intermittent Atmospheric Boundary Layer

5a. CONTRACT NUMBER
W911NF-12-1-0089

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Andreas Muschinski

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Northwest Research Associates, Inc.
4118 148th Ave. NE

Redmond, WA 98052 -5164

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
61673-EV.11

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
At the Boulder Atmospheric Observatory near Erie, CO, we have established an observational testbed for studies of turbulence and propagation in the intermittent atmospheric surface layer. We have tested and refined scientific hypotheses as well as data processing algorithms, with the goal of using optical angle-of-arrival fluctuations along horizontal, near-ground propagation paths for the remote sensing of various characteristics of atmospheric boundary turbulence, such as wind velocities, refractive-index structure parameters, and temporal fluctuations of

15. SUBJECT TERMS
atmospheric turbulence, atmospheric surface layer, optical turbulence, angle-of-arrival fluctuations

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Andreas Muschinski
					19b. TELEPHONE NUMBER
					303-415-9701

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Measurement Science of the Intermittent Atmospheric Boundary Layer

ABSTRACT

At the Boulder Atmospheric Observatory near Erie, CO, we have established an observational testbed for studies of turbulence and propagation in the intermittent atmospheric surface layer. We have tested and refined scientific hypotheses as well as data processing algorithms, with the goal of using optical angle-of-arrival fluctuations along horizontal, near-ground propagation paths for the remote sensing of various characteristics of atmospheric boundary turbulence, such as wind velocities, refractive-index structure parameters, and temporal fluctuations of the vertical temperature gradient.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
09/05/2012	1.00	Tichkule Shiril, Muschinski Andreas. Optical anemometry based on the temporal cross-correlation of angle-of-arrival fluctuations obtained from spatially separated light sources, Applied Optics, (07 2012): 5272. doi:
TOTAL:		**1**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
TOTAL:	

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
02/07/2013	4.00	Andreas Muschinski, Shiril Tichkule. Frequency spectra of optical angle-of-arrival fluctuations in the atmospheric surface layer, USNC–URSI National Radio Science Meeting. 09-JAN-13, . : ,
02/07/2013	5.00	Shiril Tichkule, Andreas Muschinski. An optical stereoscopic method for range-resolved retrieval of the cross-path wind velocity, USNC–URSI National Radio Science Meeting. 09-JAN-13, . : ,
02/07/2013	3.00	Andreas Muschinski, Shiril Tichkule. Optical Angle-of-Arrival Fluctuations Observed with Two Closely Spaced Telescopes in the Atmospheric Surface Layer, Proceedings of the 15th Annual Directed Energy Symposium. 26-NOV-12, . : ,
02/09/2013	6.00	Andreas Muschinski, Peter P. Sullivan. Using large-eddy simulation to investigate intermittency fluxes of clear-air radar reflectivity inthe atmospheric boundary layer, 2013 IEEE International Symposium on Antennas and Propagation. 07-JUL-13, . : ,
02/09/2013	7.00	Shiril Tichkule, Andreas Muschinski. An optical stereoscopic method for range-resolved retrieval of the cross-path wind velocity, 2013 IEEE International Geoscience and Remote Sensing Symposium . 21-JUL-13, . : ,

TOTAL: **5**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
03/06/2013	9.00	Andreas Muschinski, Shiril Tichkule. The Colorado Peaks Experiment, OSA Imaging and Applied Optics Congress. 24-JUN-13, . : ,
09/05/2012	2.00	Tichkule Shiril, Muschinski Andreas. Optical anemometry based on the temporal cross-correlation of angle-of-arrival fluctuations obtained from spatially separated light sources, IEEE International Geoscience and Remote Sensing Symposium -- Remote Sensing for a Dynamic Earth (22-27 July 2012, Munich, Germany). 22-JUL-12, . : ,

TOTAL: **2**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
03/06/2013	8.00	Andreas Muschinski, Shiril Tichkule, Scott Pearse. Infrasound from the Russian meteor of 15 February 2013 observed in Colorado, Geophysical Research Letters (03 2013)
12/30/2013	10.00	Shiril Tichkule, Andreas Muschinski. Effects of wind-driven telescope vibrations onmeasurements of turbulent angle-of-arrival fluctuations, Applied Optics (12 2013)

TOTAL: **2**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Justin Ayvazian	0.22	
Lucas Root	0.02	
FTE Equivalent:	**0.24**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Andreas Muschinski	0.44	No
FTE Equivalent:	**0.44**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

1 Statement of the problems studied

The overall purpose of this research program was to use optical and in situ sensors to study the merit and limitations of several hypotheses that, in combination, may serve as the backbone of a "measurement science of the intermittent atmospheric boundary layer":

- the geometrical-optics approximation (Tatarskii, 1961, 1971; Rytov et al., 1989) applied to angle-of-arrival (AOA) fluctuations of light propagating along horizontal paths through the turbulent atmosphere
- a local and instantaneous interpretation of the traditional Monin-Obukhov theory (Obukhov, 1946; Monin and Obukhov, 1954)
- a local interpretation of Taylor's frozen-turbulence hypothesis (Tatarskii, 1971)
- the theory of locally isotropic and homogeneous turbulence in velocity and scalar fields (Batchelor, 1953; Tatarskii, 1961, 1971)
- a stochastic treatment of fluctuating turbulence "parameters" such as the friction velocity, the temperature structure parameter, and the kinematic heat flux in the intermittent atmospheric boundary layer (Kolmogorov, 1962; Obukhov, 1962; Van Atta, 1971; Muschinski et al., 2004).

The motivation behind this choice of hypotheses was to avoid the (sometimes uncessary) mathematical complexities of wave optics (as opposed to geometrical optics) and thereby to make the theoretical analysis of optical wave propagation through intermittent turbulence more tractable.

2 Summary of the most important results

2.1 A quasi-operational testbed to study turbulence and propagation in the atmospheric surface layer

We decided that to establish a quasi-operational observational turbulence-and-propagation testbed at the Boulder Atmospheric Observatory near Erie, CO (which is less than 30 min away from NWRA's Boulder office) is the best way (1) to continuously improve the data quality, (2) to continuously test and refine scientific hypotheses, and (3) to accumulate an extensive database for statistical analysis and for focused case studies.

- Currently (as of the end of December 2013), the testbed consists of four portable 20-ft towers (spaced meridionally by 40 m), eight ultrasonic anemometers, two low-response thermometers, two low-response hygrometers, three quartz-crystal barometers, and two GPS-synchronized dataloggers, each of which can collect and accurately time-stamp data from up to eight sensors
- Of the five dataloggers that the PI and his students developed (Behn et al., 2008), from October 2012 through early summer 2013 three have been upgraded with new motherboards, new solid-state hard disks, new GPS synchronization software, and new GPS receivers, and they have been thoroughly field-tested since June 2013
- The testbed has been operating with eight sonics and three quartz-crystal barometers almost without interruption since June 2013

- The quartz-crystal barometers have been arranged in the form of a triangle of 40 m spacing, and the barometer array has effectively detected atmospheric infrasound (including ocean-generated "microbaroms" and the infrasound boom from the 15 February 2013 Russian meteor) and gravity waves
- During intensive-observation periods, optical AOAs and intensities have been observed with large-aperture telescopes pointing at test-light arrays located such that the propagation paths are horizontal and close to the line of sonic towers
- The test-light arrays have been refurbished and upgraded; now they include also very bright LEDs, such that daytime measurements become unproblematic (until relatively recently, we have made optical measurements only after sunset and before sunrise)
- Twice a week, we download the data collected with the continuously-operating component of the testbed and store them on a Google Drive "in the cloud" for remote and convenient access by the PI's research group and by external collaborators.

2.2 Intermittency in the atmospheric surface layer

- In spite of severe intermittency at time scales between tens of seconds and tens of minutes, in most cases the 1-min estimates of the sensible heat flux observed at 1.45 m and 2.15 m AGL agree very well with each other, which is consistent with the constant-flux hypothesis (one of the underlying hypotheses of the Monin-Obukhov theory)
- Time series of 1-min estimates of sensible heat fluxes and 1-min temperature sample means observed with two vertically spaced sonics can be used for post-facto calibration (Muschinski and Ayvazian, 2014) of relative biases in a pair of ultrasonic thermometers with an accuracy (about 10 mK) that is very similar to the accuracy that can be achieved on a calibration stand that is populated with multiple sonics at the same height
- Sonic measurements at single points and path-averaging (150 m) optical measurements track each other well down to time scales of 1 min, sometimes down to 10 s (e.g., Tichkule and Muschinski, 2012).

2.3 Optical remote sensing by means of AOA fluctuations

AOA fluctuations observed with horizontally pointing 36-cm telescopes can be used to retrieve robust 1-min estimates of path-averages (150 m)

- of the optical refractive-index structure parameter, C_n^2
- of beam-transverse wind velocities
- of temporal fluctuations of the vertical temperature gradient.

2.4 Frequency spectra of AOA fluctuations

- In practically all AOA spectra that we have observed, there is a robust $f^{-8/3}$ power law at frequencies large compared to the "knee frequency" V/D associated with the aperture-filter cutoff, where V is the mean beam-transverse wind speed and D is the aperture diameter.

The $-8/3$ law was predicted by Tatarskii (1971) for plane waves and by Clifford (1971) for spherical waves

- The spectral ratio $S_\alpha(f)/S_\beta(f)$ [where α is the vertical AOA and β is the horizontal AOA] appears to independent of f within the $-8/3$ regime, but the value of that ratio appears to reflect anisotropy in the velocity field, rather than anisotropy in the temperature field

2.5 AOA artifacts resulting from wind-driven telescope vibrations

As an alternative to our heavy, 36-cm telescopes ($7,000 a piece), we studied the performance of light-weight, inexpensive, 11-cm telescopes ($200 a piece). In order to understand their vulnerability to wind-driven vibrations, we exposed them deliberately to the wind (Tichkule and Muschinski, 2013).

- The observed AOA spectra are contaminated by wind-driven vibrations in narrow frequency bands
- The resonance frequencies are constant; in particular they are independent of the wind speed
- The observed AOA rms value σ_{AOA} resulting from a wind-driven telescope resonance appears to be consistent with the scaling law (Tichkule and Muschinski, 2013)

$$\sigma_{\mathrm{AOA}} \sim \frac{D\rho}{M f_r^2} U^2, \tag{1}$$

  where f_r is the resonance frequency, D is the telescope's aperture diameter, M is the telescope's mass, ρ is the air density, and U is the wind speed
- Because the telescope vibrations contaminate the turbulent AOA flucutations only within narrow frequency bands, there is hope that frequency-domain estimators can be designed that enable one to obtain meaningful AOA statistics even in the case of severe, wind-driven telescope vibrations.

Bibliography

Batchelor, G. K., 1953: *The theory of homogeneous turbulence*. Cambridge University Press, Cambridge.

Behn, M., V. Hohreiter, and A. Muschinski, 2008: A scalable data-logging system with serial interfaces and integrated GPS time-stamping. *J. Atmos. Oceanic Technol.*, **25**, 1568–1578.

Clifford, S. F., 1971: Temporal-frequency spectra for a spherical wave propagating through atmospheric turbulence. *J. Opt. Soc. Am.*, **61**, 1285–1292.

Kolmogorov, A. N., 1962: A refinement of previous hypotheses concerning the local structure of turbulence in a viscous incompressible fluid at high Reynolds number. *J. Fluid Mech.*, **13**, 82–85.

Monin, A. S., and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the atmosphere near the ground. *Trudy Geofiz. Inst. Akad. Nauk. SSSR*, **24**, 163–187.

Muschinski, A., and J. Ayvazian, 2014: Post-facto calibration of relative temperature biases measured with pairs of vertically spaced sonics in the atmospheric surface layer. *Boundary-Layer Meteorol.,* in preparation for submission.

Muschinski, A., R. G. Frehlich, and B. B. Balsley, 2004: Small-scale and large-scale intermittency in the nocturnal boundary layer and the residual layer. *J. Fluid Mech.*, **515**, 319–351.

Obukhov, A. M., 1946: Turbulence in a thermally inhomogeneous atmosphere. *Trudy In-ta Teoret. Geofiz. AN SSSR*, **1**, 95–115.

Obukhov, A. M., 1962: Some specific features of atmospheric turbulence. *J. Fluid Mech.*, **13**, 77–81.

Rytov, S. M., Y. A. Kravtsov, and V. I. Tatarskii, 1989: *Principles of statistical radio physics – 4. Wave propagation through random media.* Springer, Berlin, Germany.

Tatarskii, V. I., 1961: *Wave propagation in a turbulent medium.* McGraw-Hill, New York.

Tatarskii, V. I., 1971: *The effects of the turbulent atmosphere on wave propagation.* Israel Program for Scientific Translation, Jerusalem, Israel.

Tichkule, S., and A. Muschinski, 2012: Optical anemometry based on the temporal cross-correlation of angle-of-arrival fluctuations obtained from spatially separated light sources. *Appl. Opt.*, **51**, 5272–5282.

Tichkule, S., and A. Muschinski, 2013: Effects of wind-induced telescope vibrations on observations of optical angle-of-arrival fluctuations in the atmospheric surface layer. *Appl. Opt.,* submitted in December 2013.

Van Atta, C. W., 1971: Influence of fluctuations in local dissipation rates on turbulent scalar characteristics in the inertial subrange. *Phys. Fluids*, **14**, 1803–1804.